Principles of climate modeling

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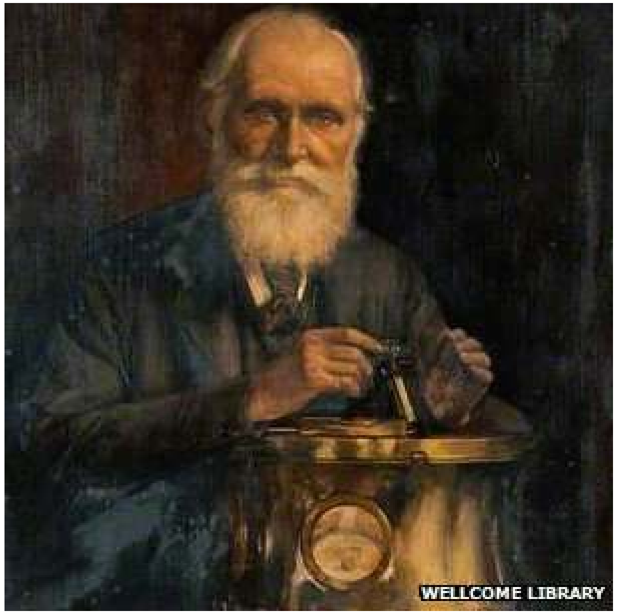
I. Context and principles
→ Numerical modeling
→ Climate change context
→ Basis of climate modeling

II. General circulation models
→ Primitive equations
→ Parameterizations

III. Climate system modeling
→ Numerical weather forecast versus climate
→ Splitting into sub-systems
→ Advection/Diffusion

About models in physics



From William Thomson, Lord Kelvin
1824 – 1907

I can never satisfy myself until I can make a mechanical model of a thing. ***If I can make a mechanical model, I can understand it****. As long as I cannot make a mechanical model all the way through I cannot understand.*

Can you measure it? Can you express it in figures? Can you make a model of it? If not, your theory is apt to be based more upon imagination than upon knowledge.

https://crev.info/scientists/william-thomson-lord-kelvin/

The 5 layers of numerical modeling

Models before computers

Appearences
The world in which you describe phenomenas
Obseravtions, measures, experiments

Theories
In physics, chemistry, biology, chemistry

équations
Mathematical translation of theories
Solutions of the equations can be compared with observations and used for prediction

Many mathematical models exists the solutions of which were impossible to compute before the arrival of computers except in very simple cases

Numerics
Translation into equations that can be implemented in computers (in particular finite dimension). Sill “on paper”

Computers
Algorithmes, boucles, langages, optimisation, adaptation aux calculateurs, post-traitements
The world of numerical simulations

Numerical simulations can be compared with observations and used for prediction

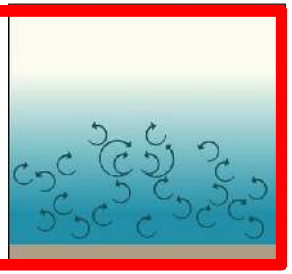
The 5 layers of numerical modeling

Models before computers

Appearences
Storms , trade winds, seasonal cycle of temperature and rainfall, global warming, **pollutant dispersion**...




Theories
Fluid mechanics, thermodynamics material-radiation interaction, radiative transfer, **turbulence**

équations
Mathematical translation of theories

Navier-Stokes

$$\rho\frac{D\vec{V}}{Dt} = -\nabla p + \rho\vec{g} + \mu\nabla^2\vec{V}$$

Radiative tranfer

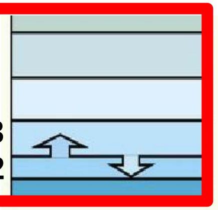
$$\mu\frac{\partial I_\nu(r,\mu)}{\partial r} + \frac{1-\mu^2}{r}\frac{\partial I_\nu(r,\mu)}{\partial \mu} = -\kappa_\nu(r)\,I_\nu(r,\mu) - \bar{s}_\nu(r)\,I_\nu(r,\mu) + \eta_\nu^{\rm ind}(r)\,I_\nu(r,\mu) + \eta_\nu^{\rm sp}(r) + \frac{1}{4\pi}\int_{-1}^{+1}\int_0^{2\pi} I_\nu(r,\mu')\,s_\nu(r,\mu,\mu';\phi,\phi')\,{\rm d}\mu'\,{\rm d}\phi'$$

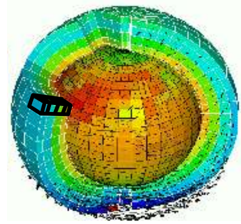
Turbulent diffusion

$$F_q(z) = -K_z\frac{\partial q}{\partial z}$$

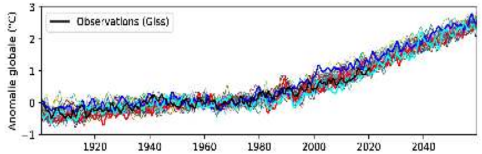
Numerics
Grid point or spectral methods, **finite differences**/volumes, conservation and accuracy issues

$$F_{2-3} = K_{2-3}(q_2 - q_3)$$





<u>Computers</u>
Algorithmes, boucles, langages, optimisation, adaptation aux calculateurs, post-traitements

The world of numerical simulations

About models in climate sciences

A specific context :

→ Predict the unique climate evolution from the present day climate

→ Complex system, some laws of which are not known a priori (climate feedbacks)

→ System sensitive to initial conditions (chaos, strange attractor, etc ...)

Various approaches in terms of modeling :

→ Simple models, developed to explore a particular mechanism or process (Lorentz model, 1D models of radiative/convective equilibrium, …)

→ Fine grid simulations of cloud processes (LES)

→ General circulation models

3D modeling which will be discussed here : **General circulation models**

→ Pursuit of a kind of exaustivity

→ Pursuit of « realism »

→ Built on physical principles

General philosophy (Charney 1950) :

work with incomplete and imperfect tools and improve them step by step

General circulation models : elements of history

Physics theories known from the XIXst century, but impossible to compute solutions relevant for the atmosphere

1950-1960 : first computers ; first models for weather forecast

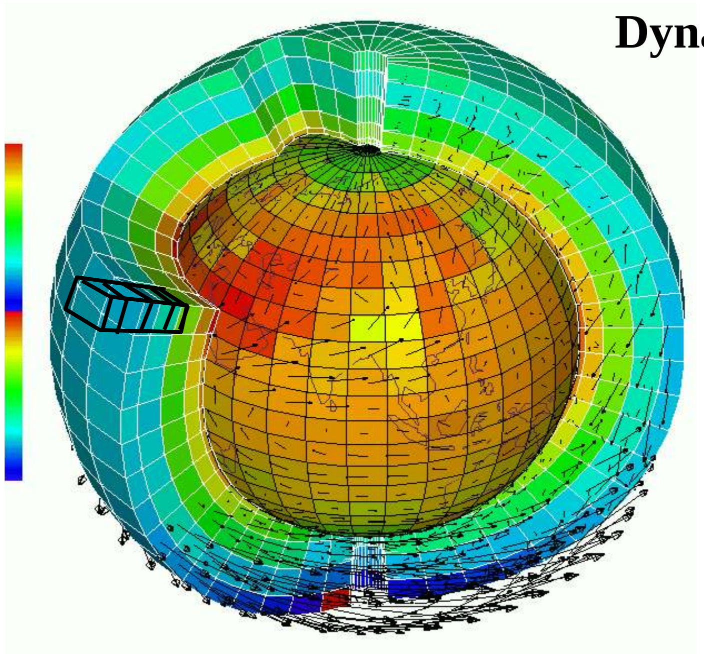
1960-1970 : first climate models

1970-1980 : first models coupling atmosphere and oceans

1979 : First simulations predicting global warming.
Charney's report (US)

1988 : Creation of IPCC whose assessment reports rely on a large part of projections with global climate models coordinated in the Coupled Model Inter-comparison Projects, CMIP

General circulation model : fluid dynamics



Dynamical core : primitive equations discretized on the sphere

- Mass conservation

  $D\rho/Dt + \rho \, \mathrm{div}\underline{U} = 0$
- Potential temperature conservation

  $D\theta / Dt = 0$
- Momentum conservation

  $D\underline{U}/Dt + (1/\rho)\, \underline{\mathrm{grad}p} - \underline{g} + 2\, \underline{\Omega} \wedge \underline{U} = 0$
- Secondary components conservation

  $Dq/Dt = 0$

Primitive equations of meteorology

→ Thin layer approximation

→ Hydrostatic approximation (**valid down to 10-20 km**)

→ General enough to be used for other planetary atmospheres

From physics to numerics :

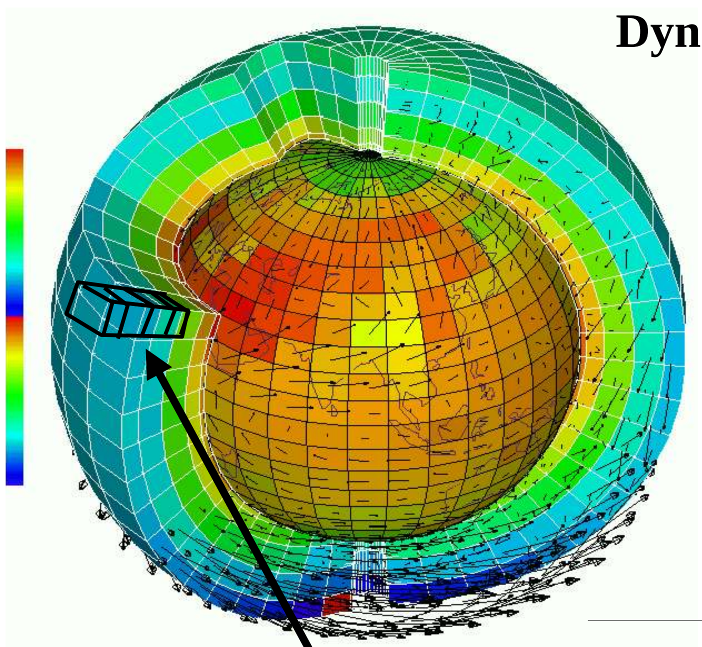
→ Grid point or spectral models

→ Explicit resolution down to 20-300 km depending of the configuration

→ Numerical conservation of important quantities (mass, water, enstrophy ...).

II. General circulation models

Dynamical core : primitive equations discretized on the sphere



- Mass conservation

  $D\rho/Dt + \rho\,\mathrm{div}\underline{U} = 0$

- Potential temperature conservation

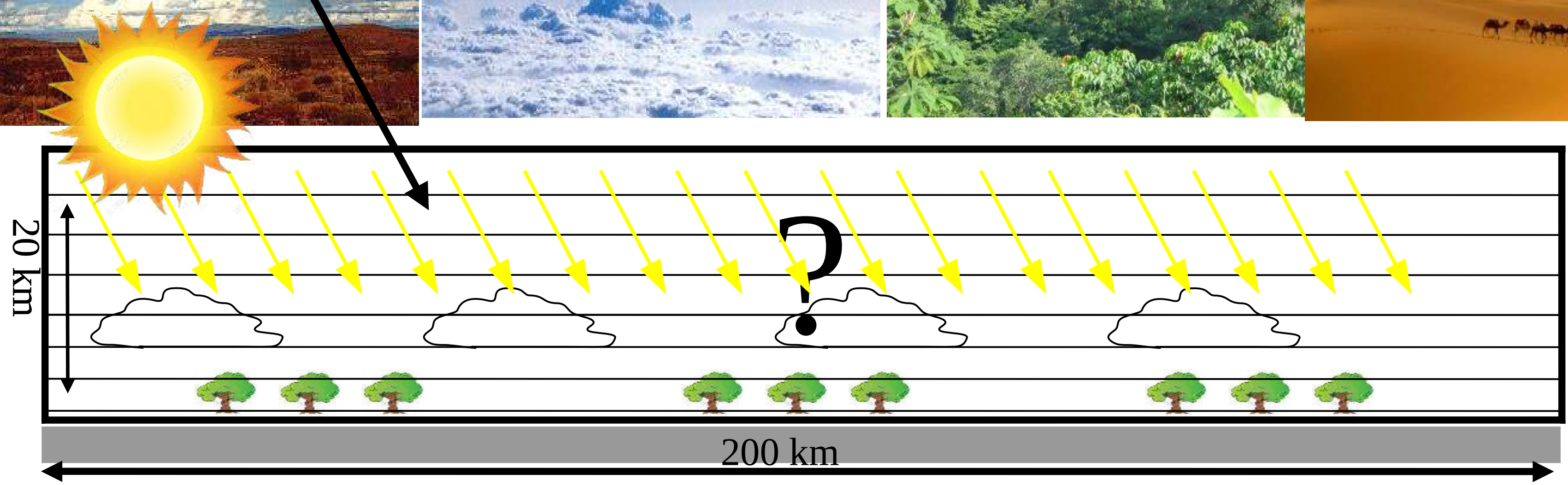
  $D\theta\,/\,Dt = Q\,/\,Cp\;(p0/p)^{\kappa}$

- Momentum conservation

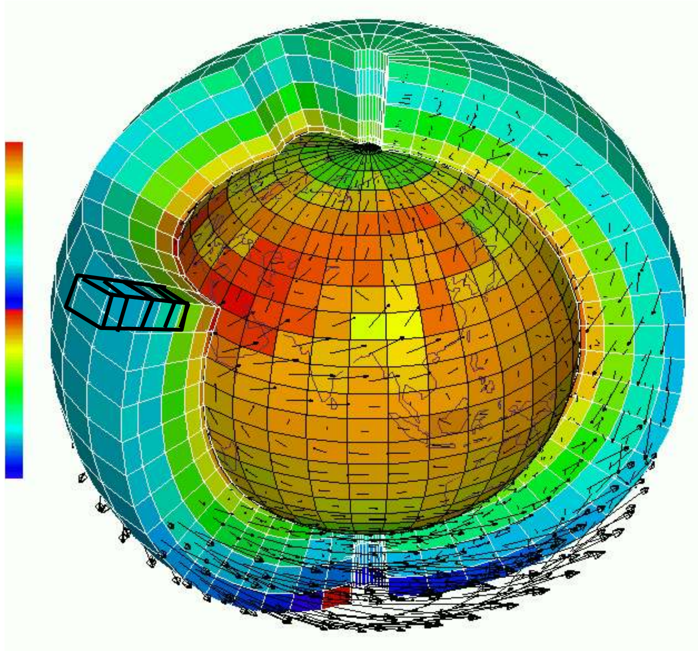
  $D\underline{U}/Dt + (1/\rho)\,\underline{\mathrm{grad}p} - \underline{g} + 2\,\underline{\Omega}\,\wedge\underline{U} = \underline{F}$

- Secondary components conservation

  $Dq/Dt\; = Sq$



II. General circulation models



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- Secondary components conservation

  $Dq/Dt = Sq$

Parameterizations purpose : account for the effect of processes non resolved by the dynamical core

→ **Traditional « source » terms in the equations**

- *Q* : Heating by radiative exchanges, thermal conduction (neglected), condensation, sublimation, **subgrid-scale motions (turbulence, clouds, convection)**

- *F* : Molecular viscosity (neglected), **subgrid-scale motions (turbulence, clouds, convection)**

- *Sq* : condensation/sublimation (q= water vapor or condensed), chemical reactions, photo-dissociation (ozone, chemical species), micro physics and scavenging (pollution aerosols, dust, ...), **subgrid-scale motions (turbulence, clouds, convection)**

Parameterizations : principles




- Compute the **average effect of unresolved processes on the global model state variables** ($\underline{U}$, θ, q)

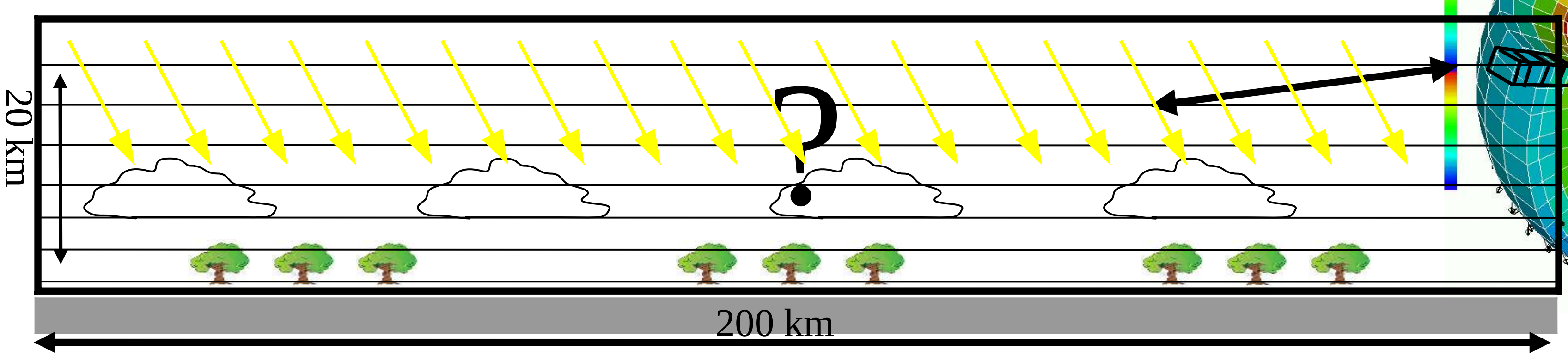
- **Based on a description of the approximate collective behavior** of processes

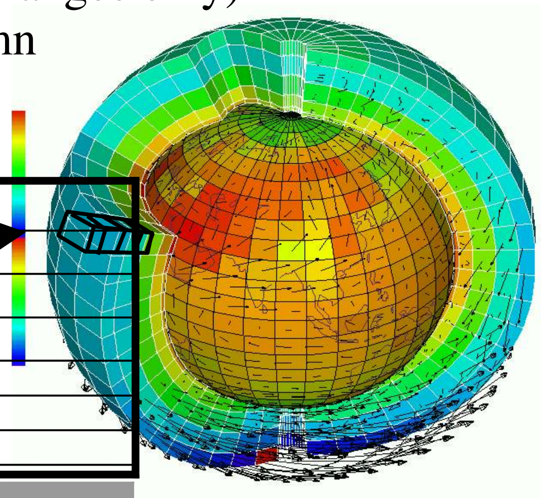
- Involve additional **parameterization internal variables** (cloud characteristics, standard deviation of the sub-grid scale distribution of a variable, …)

- Derive **equations** relating internal variables to the state variables
  $\underline{U}$, θ, q at time t → **internal variables** → $\underline{F}$, Q, Sq → $\underline{U}$, θ, q at t+δt

- **Homogeneity hypothesis** (statistical) on the horizontal of the targeted processes (like in the plane-parallel approximation of radiative transfer)
  → 1-dimensional equations in z (vertical exchanges only)
  → Independent atmospheric column

Inside an « atmospheric column » …





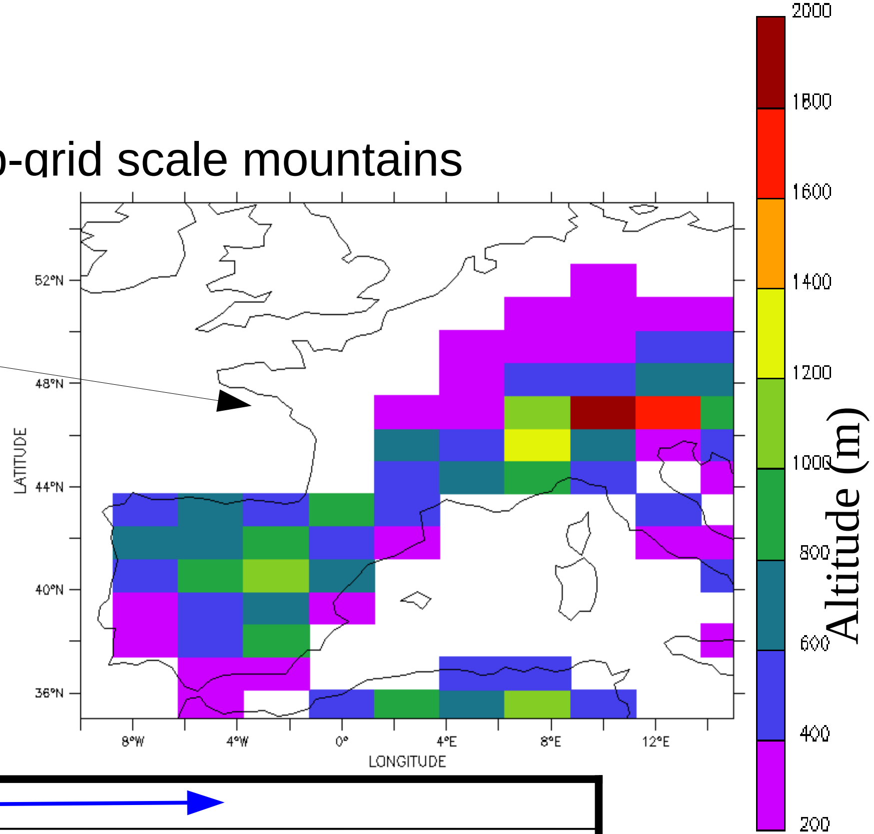
II. General circulation models

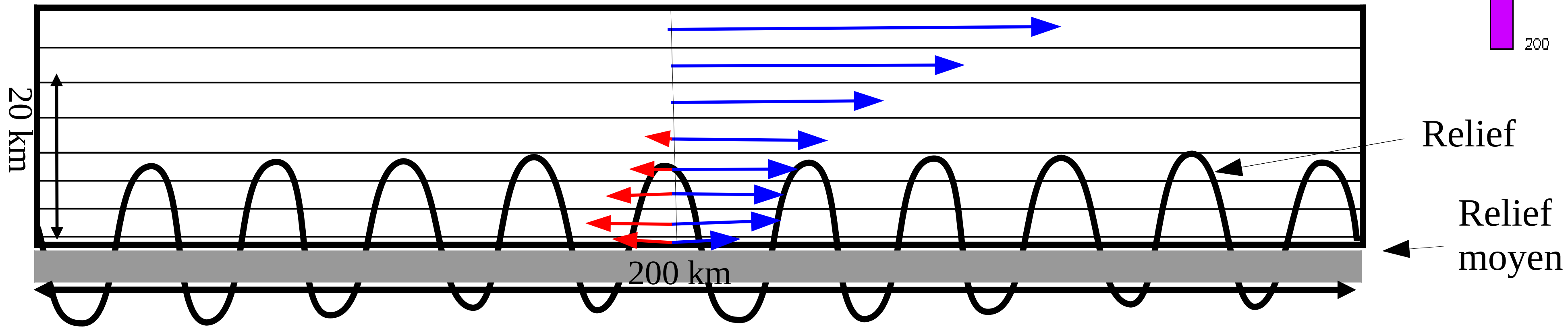
Example of sub-grid scale process : sub-grid scale mountains

→ The averaged surface height is taken into account as a boundary condition at the lower boundary
→ This averaged height does not take into account the barrier effect associated with the highest mountains.
→ Simple example of a parameterization of this aspect : introduction of a drag in the first atmospheric layers

$$D\underline{U}/Dt + (1/\rho)\,\underline{\mathrm{grad}p} - \underline{g} + 2\,\underline{\Omega}\,\wedge\underline{U} = \underline{F}$$

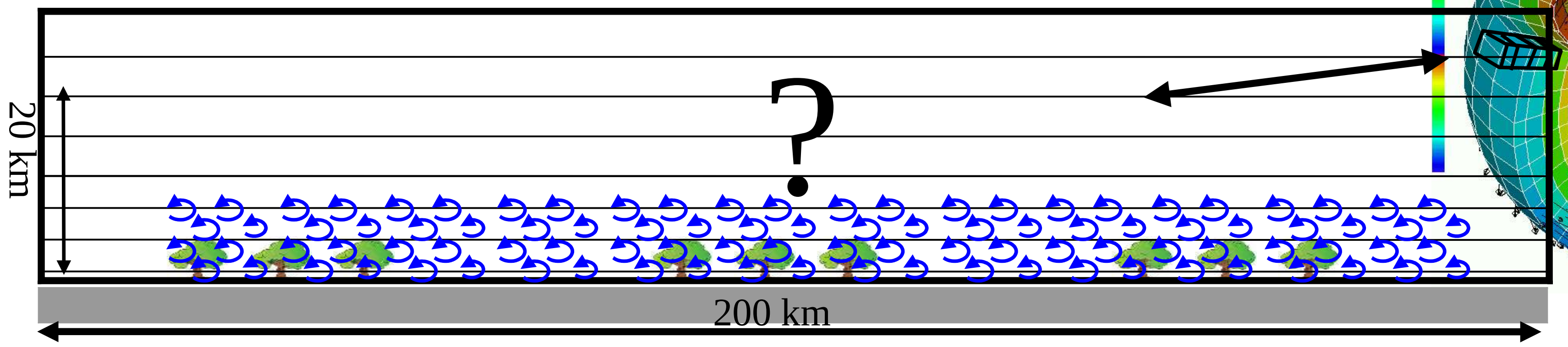
$$\underline{F} = -a\,(z)\,\underline{U}$$

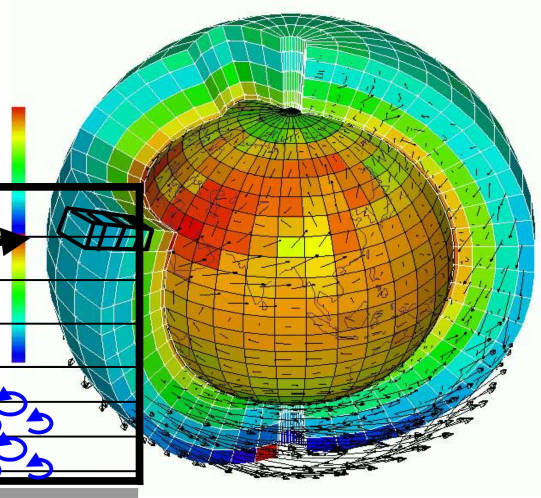




In state-of-the-art models :
→ Injection of gravity waves
→ bypassing (contournement) effects
→ stability (conditioning the ability of the air to flow over a mountain)
...

Within a column of the atmospheric model ...





la turbulence

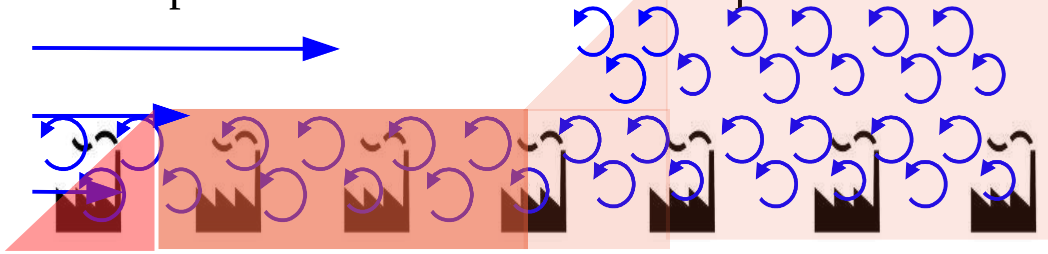
- Small scale random motions (gusts)

- Important close to the surface(1-3 km) in the boundary layer (during a plane takeoff).

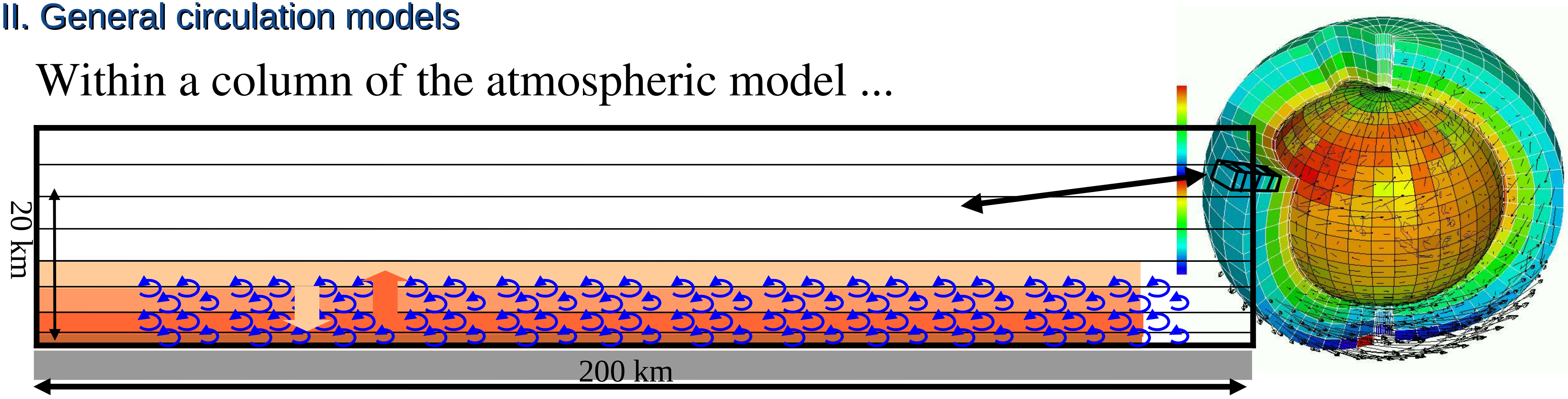
- Source : drag on obstacles + heating by the surface

- Responsible for vertical mixing of atmospheric constituents.

- Stable atmosphère → weak turbulence → pollution



Within a column of the atmospheric model ...



Turbulence parameterization

→ **« turbulent mixing»** or turbulent diffusion
Transport by small random motions.
Analogous to molecular diffusion

$Dq/Dt = Sq$ with $Sq = \frac{\partial}{\partial z}\left(K_z \frac{\partial q}{\partial z}\right)$

→ Prandtl mixing length : $K_z = l|w|$

l : Caracteristic mixing length

w : Caracterisitc velocity

→ Turbulent kinetic energy : $K_z = l\sqrt{e}$

De/Dt = f (dU/dz, dθ/dz,e,...)

Dl/dt= ...

A world by itself

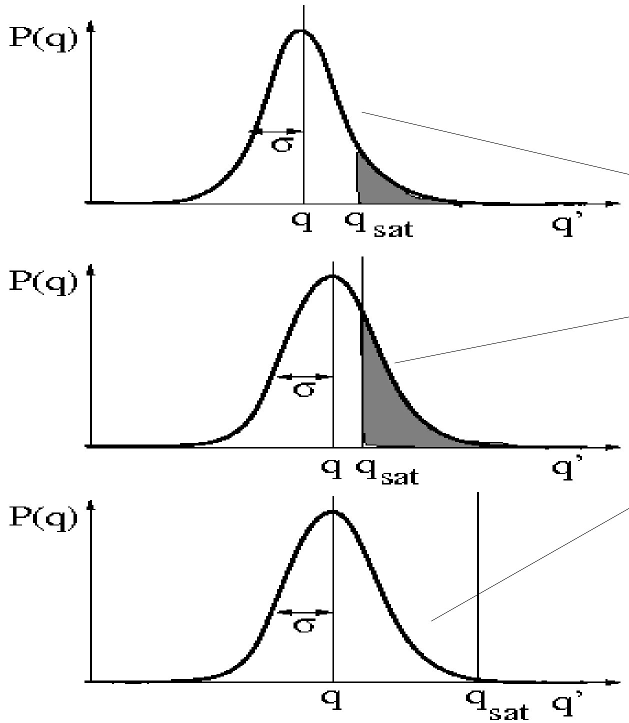
Same models are used in ingineering sciences

Similarity → Tests à des échelles différentes en laboratoire

II. General circulation models

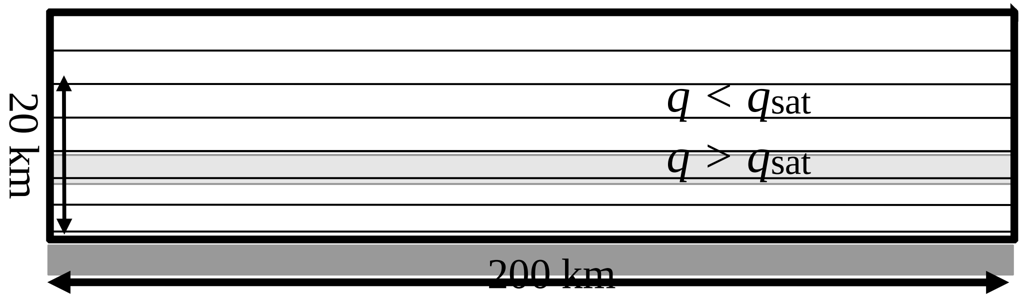
Representation of clouds

q : water vapor concentration
q_{sat} : maximum concentration at saturation
If $q > q_{sat}$:
→ water condenses = clouds
q *and* q_{sat} are known at the grid scale
→ What is the fractional coverage ?

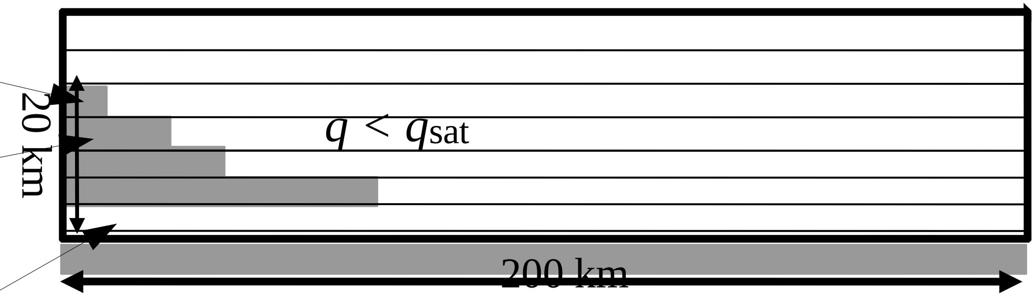


Simple parameterization : gaussian with $\sigma / q = 20\%$

« all or nothing » model :
If $q > q_{sat}$ cloudy grid cell, else clear sky



« Satistical » cloud scheme :
We assume a subgrid-scale distribution of q' in the grid cell centered on q



II. General circulation models

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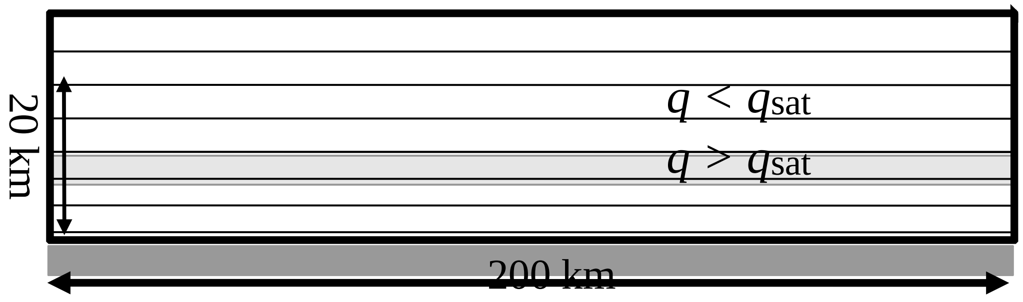

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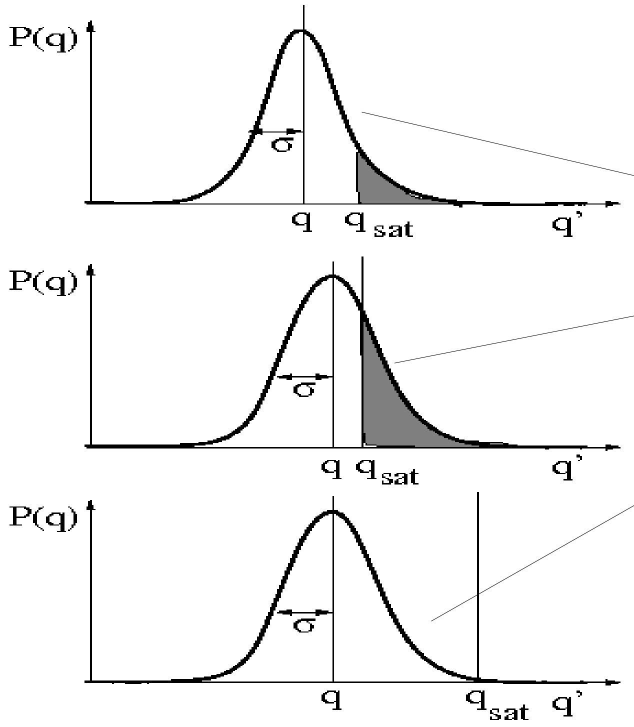
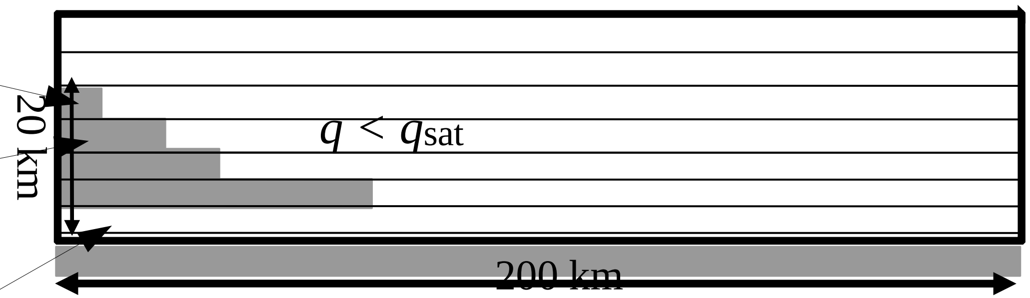
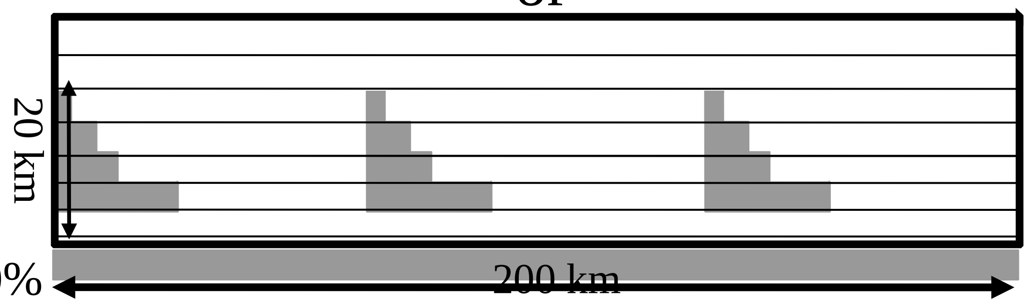




or



Simple parameterization : gaussian with $\sigma / q = 20\%$

II. General circulation models

In the world of numerical models

Before computers

Appearances :
Meteorology, climate, atmospheric composition

Theories :
Fluid mechanics, Gas/radiation interaction, Thermodynamics, Chemistry

Mathematics
Primitive equations, Thermodynamical laws, Radiative transfer equations

Numerics
Grid point discretization, spectral methods, Finite volume and finite differences
conservation, robustness and efficiency, rather than accuracy

Computers
Fortran/Linux, High Performance Computing, Flexibility/Multi-configuration, post-processing

Dynamcial core

parameterizations

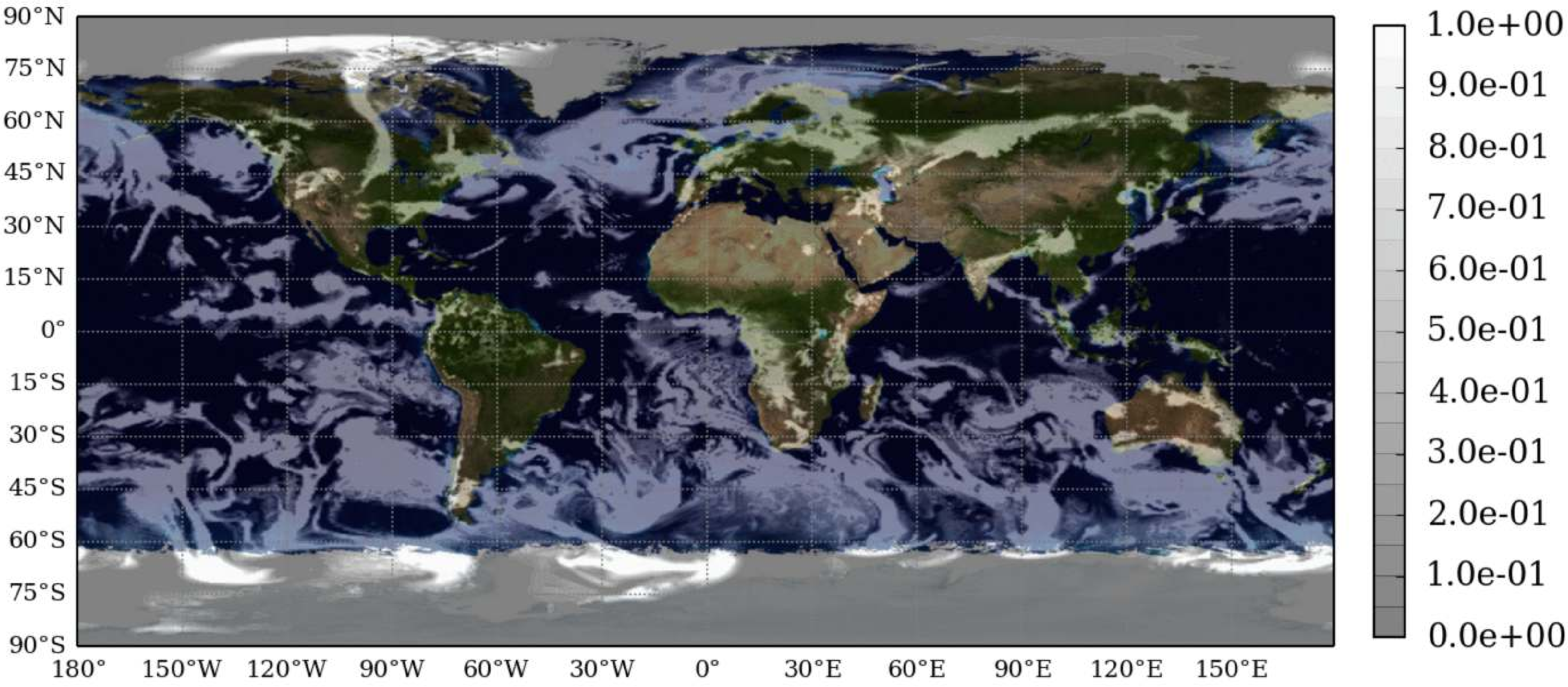
Dynamical core :
Well established equations. Work on approximations, numerics, HPC

Parameterizations :
Based on combinations of theories, heuristic approaches, and conservation laws.
Many ways possible. Strong diversity across models

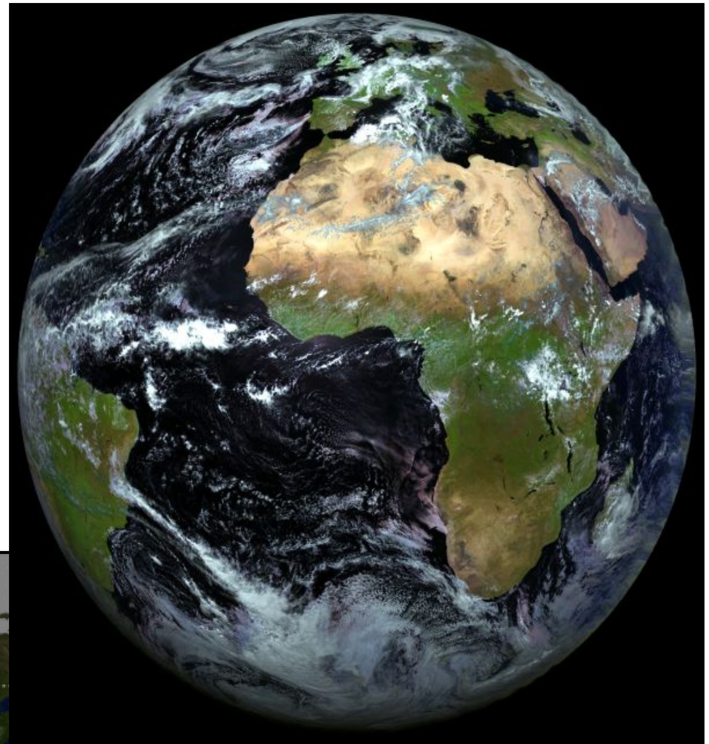
General comments :

- Modeling concerns all the layers. Lot of expertises required and shared.
- Be aware of the layer in which you are working, or at which transition between layers.
- Do not forget that your goal is to explain things in the first layer

Low clouds simulated with LMDZ with a global 50km resolution grid
January



Meteosat observation of clouds



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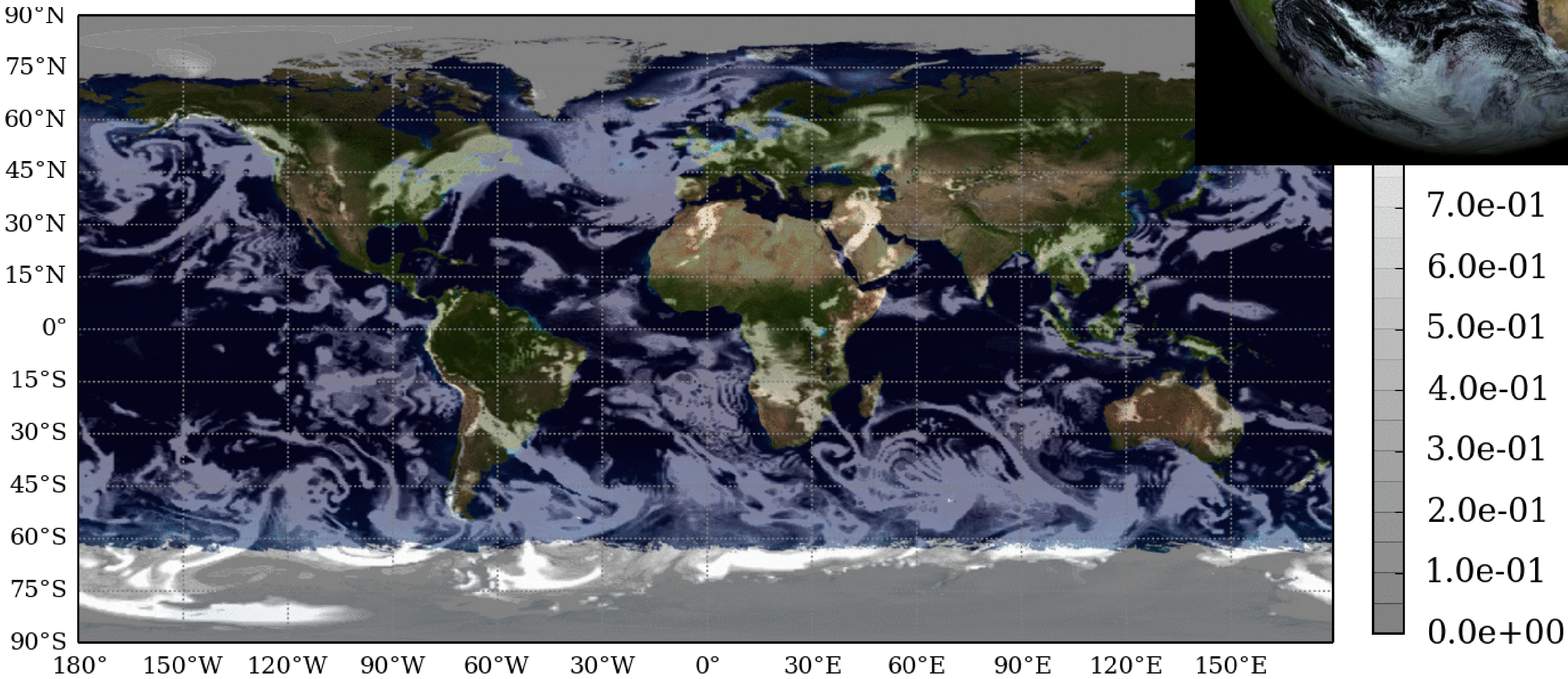
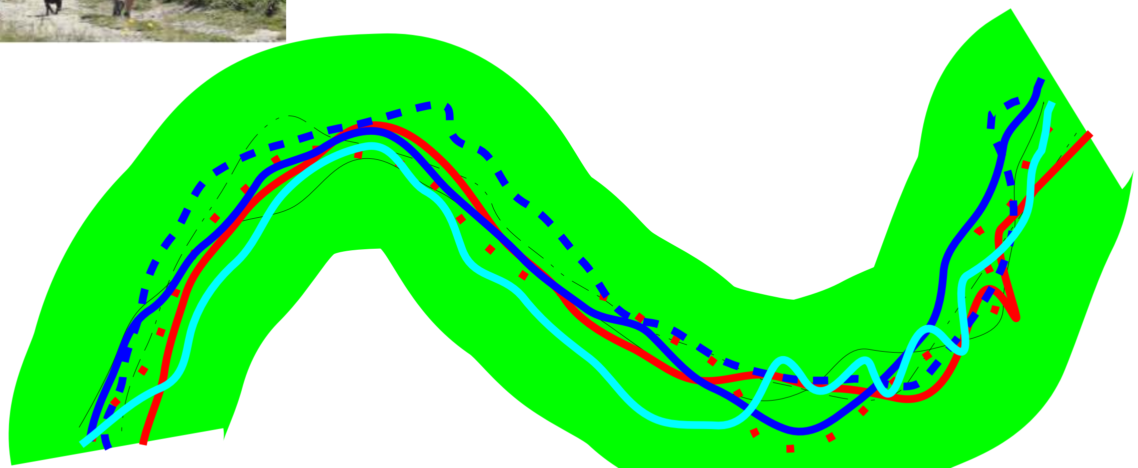


III. Climate system modeling

	Climate modeling	Numerical Weather Forecast
Models	Identical (more couplings)	Identical (higher resolution)
Initial state	any	"**analysis**" obtained form an "assimilation" of observations within a model.
Simulation length	decades to centuries	15 days (Seasonal forecast in between)
Prediction	statistical (ex : mean temperature, internal variability of precipitation, heat waves) Strange attractor = climate	deterministic (the weather tomorrow at a given location)



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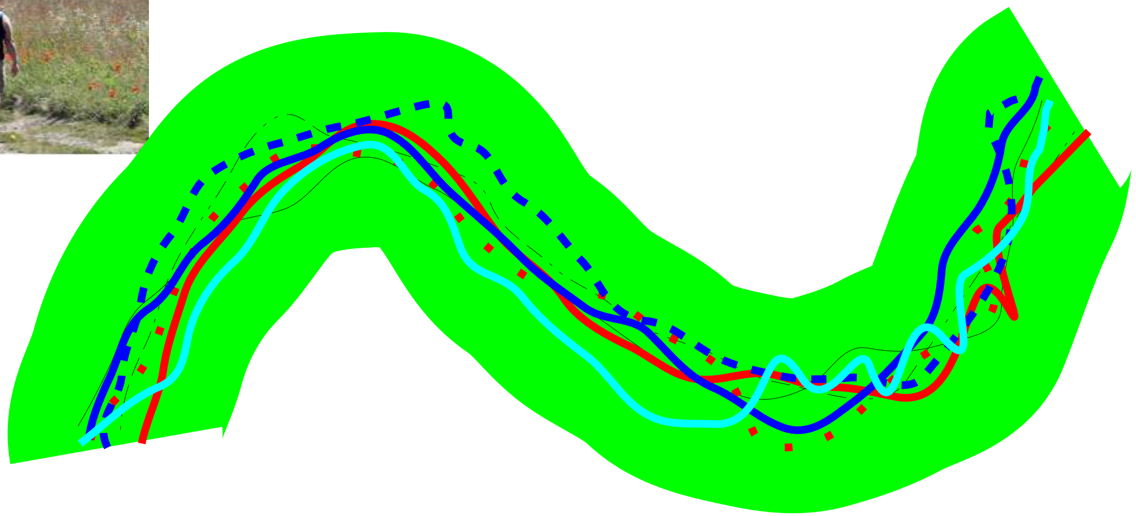
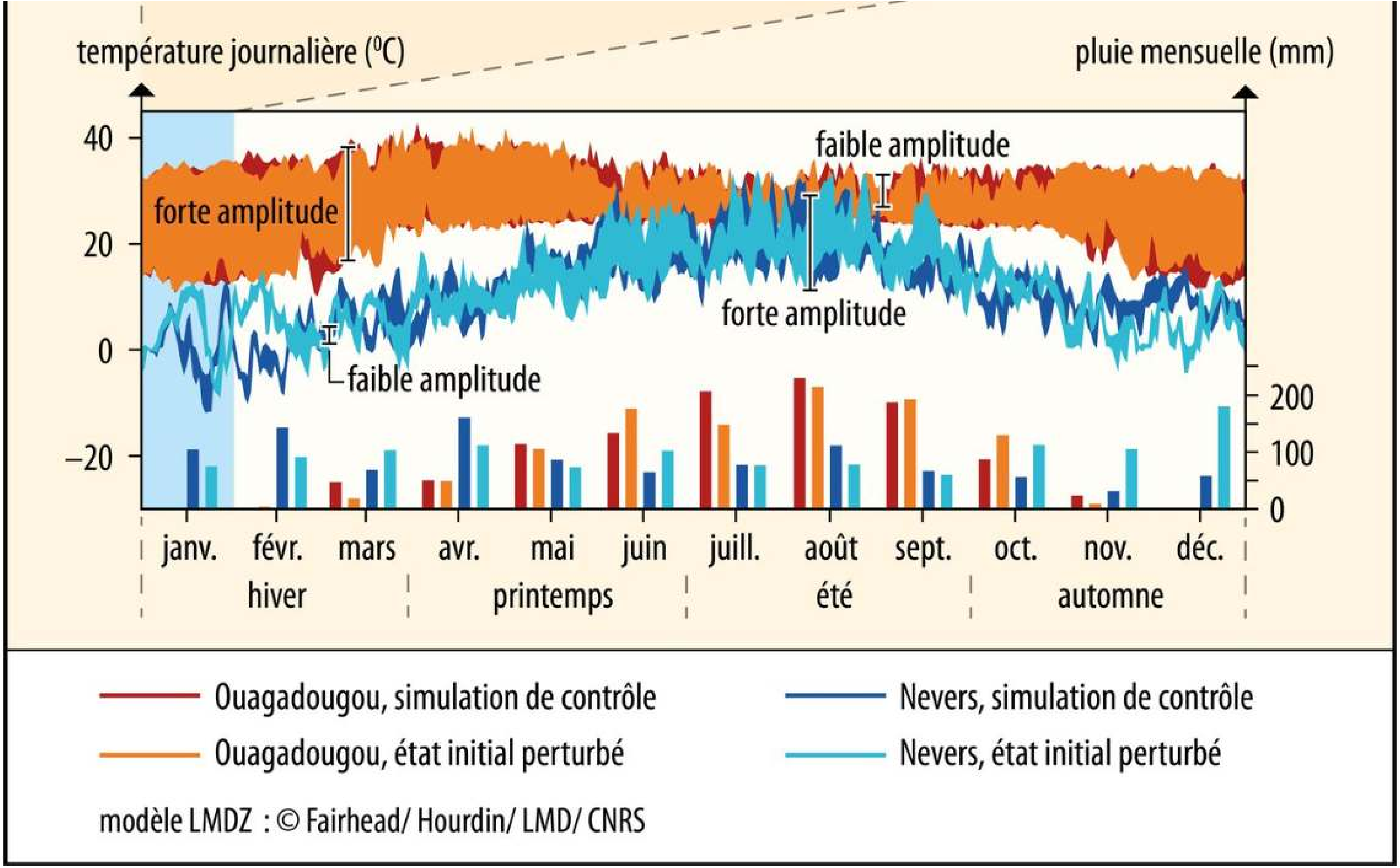
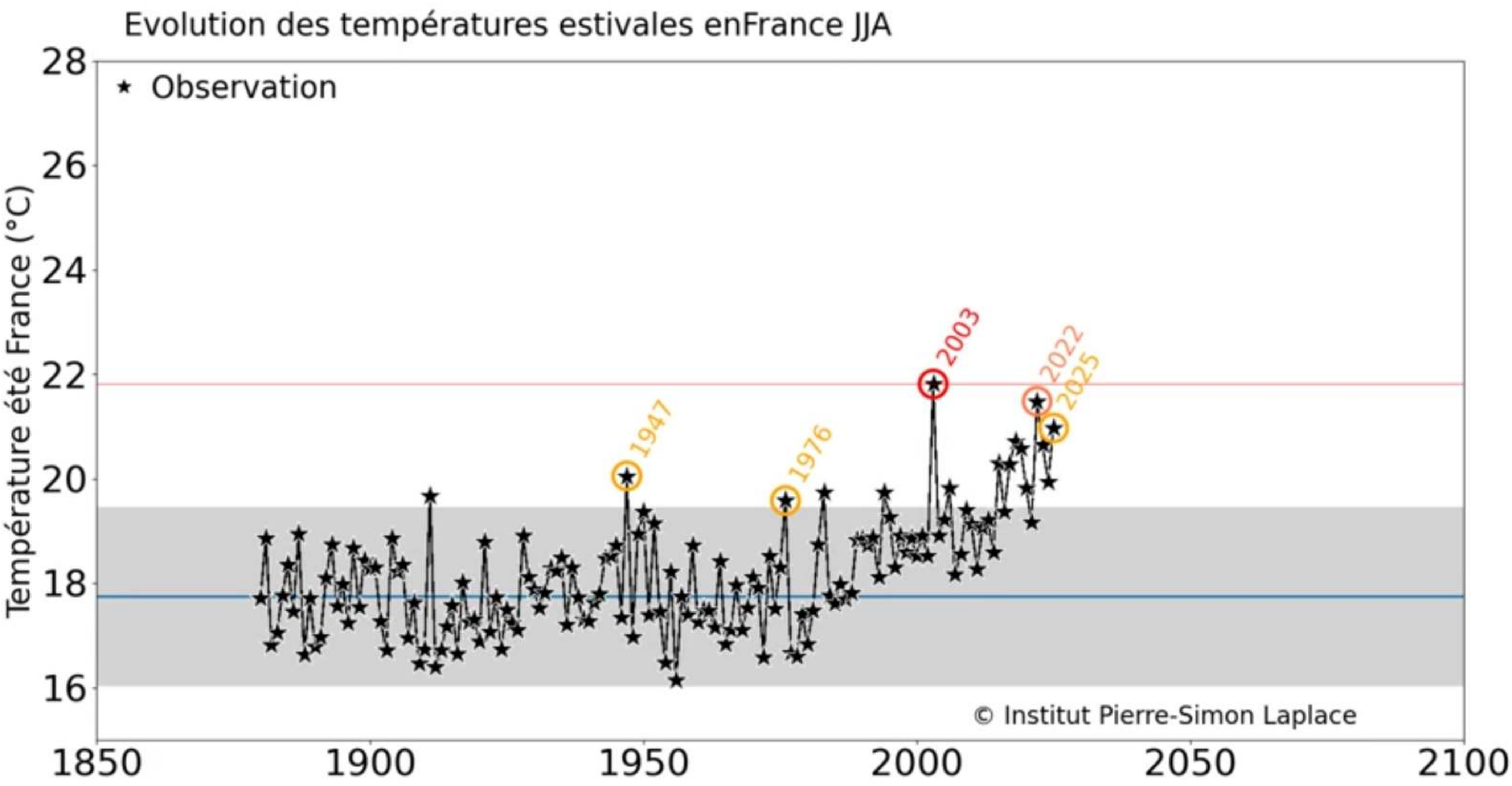




2 simulations d'un an réalisées avec le modèle LMDZ en perturbant aléatoirement l'état initial de la température avec un bruit d'amplitude 0.1

Tiré d'un chapitre de l'encyclopédie Universalis sur la 5« Modélisation du climat »
Hourdin et Guillemot (2021)
https://web.lmd.jussieu.fr/~hourdin/PUBLIS/HourdinGuillemotUniversalis.pdf

III. Climate system modeling



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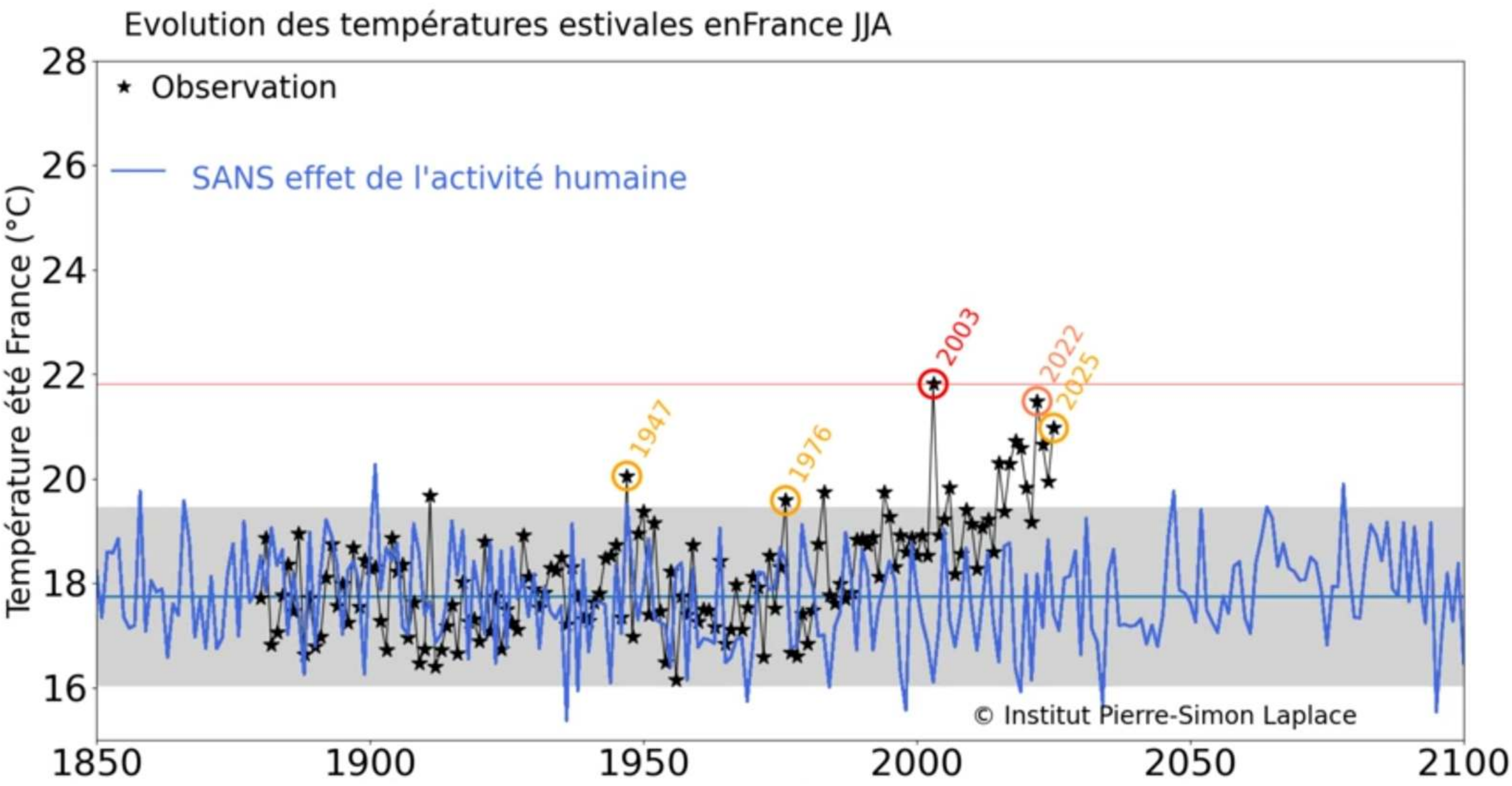

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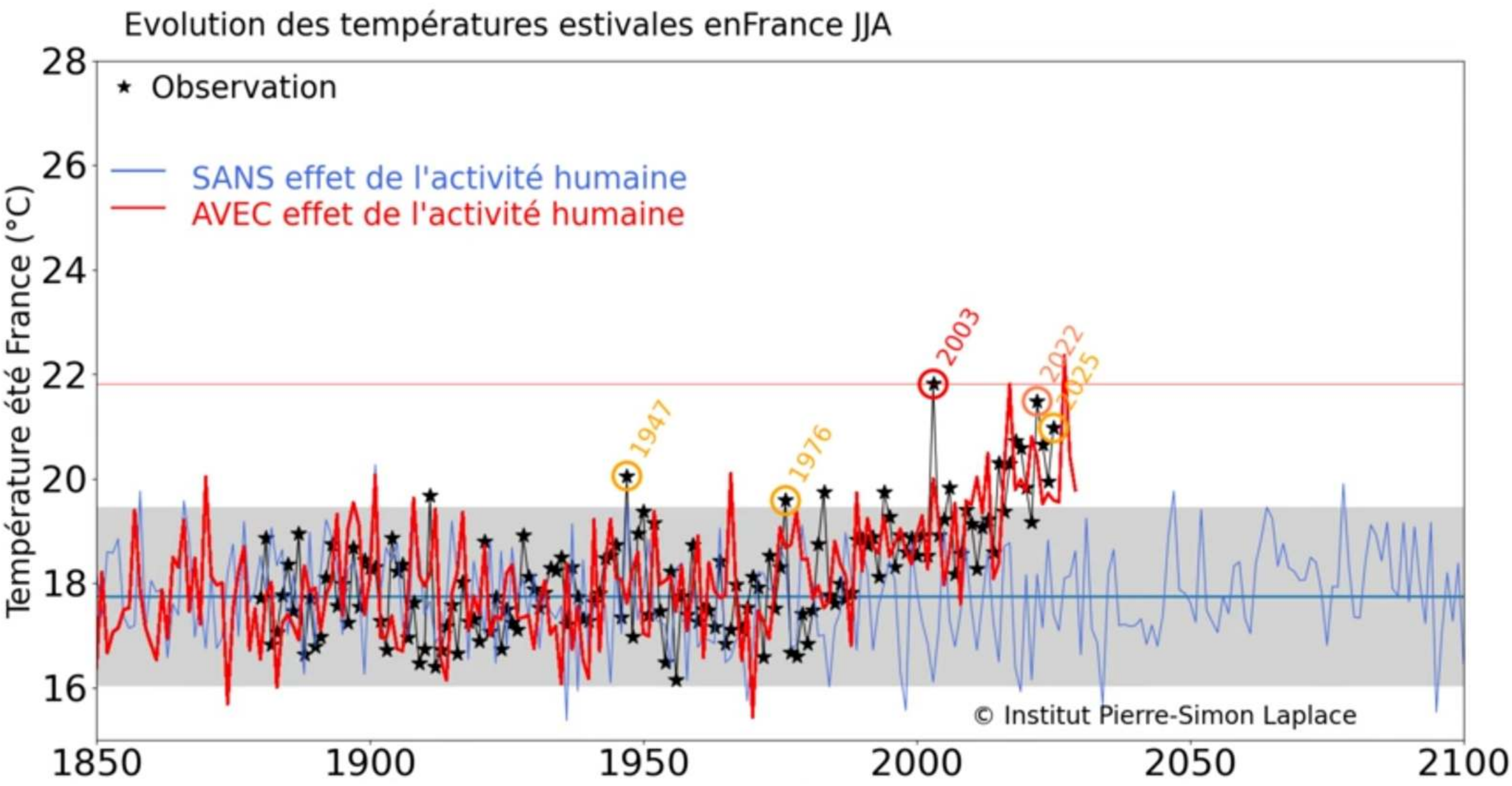

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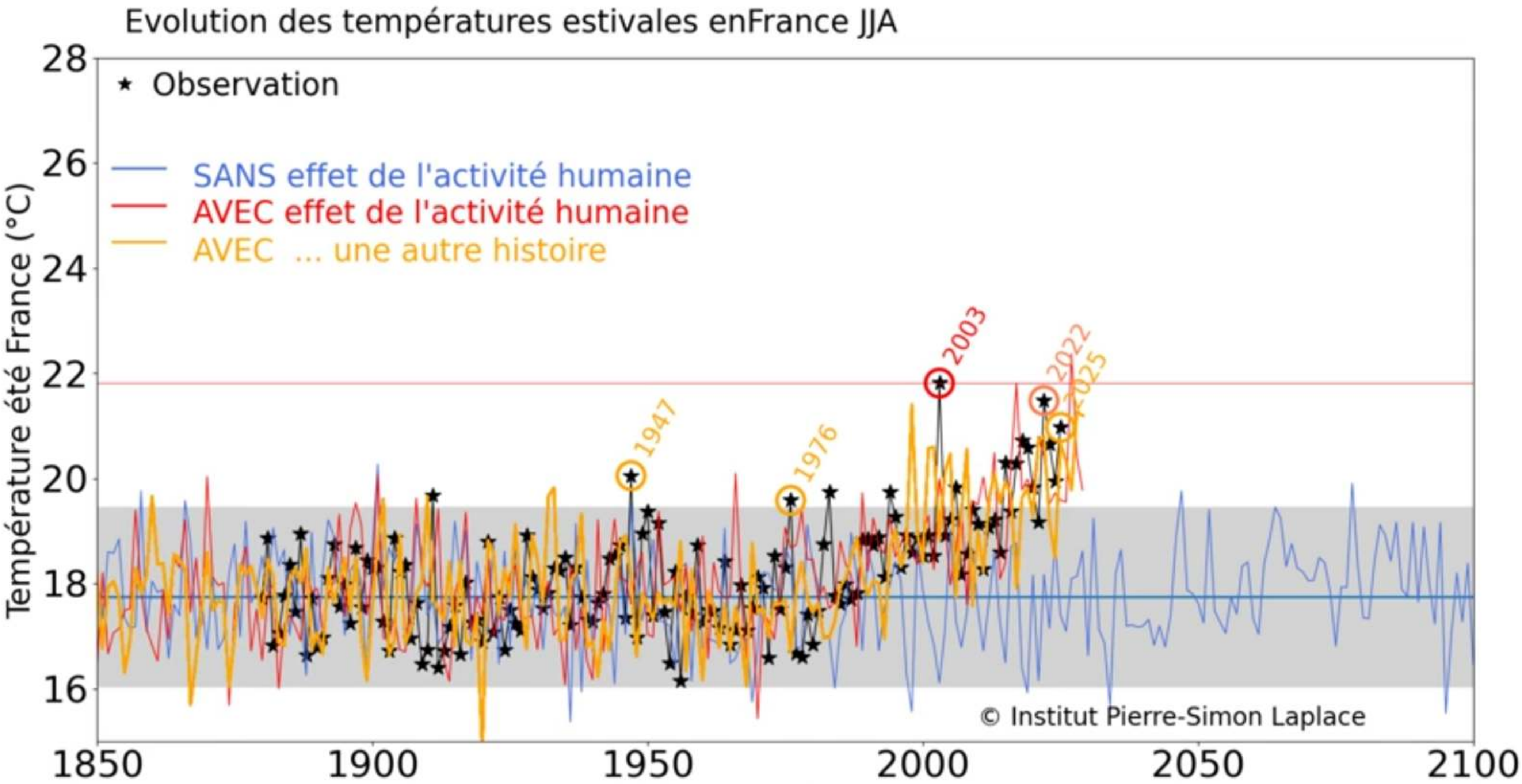

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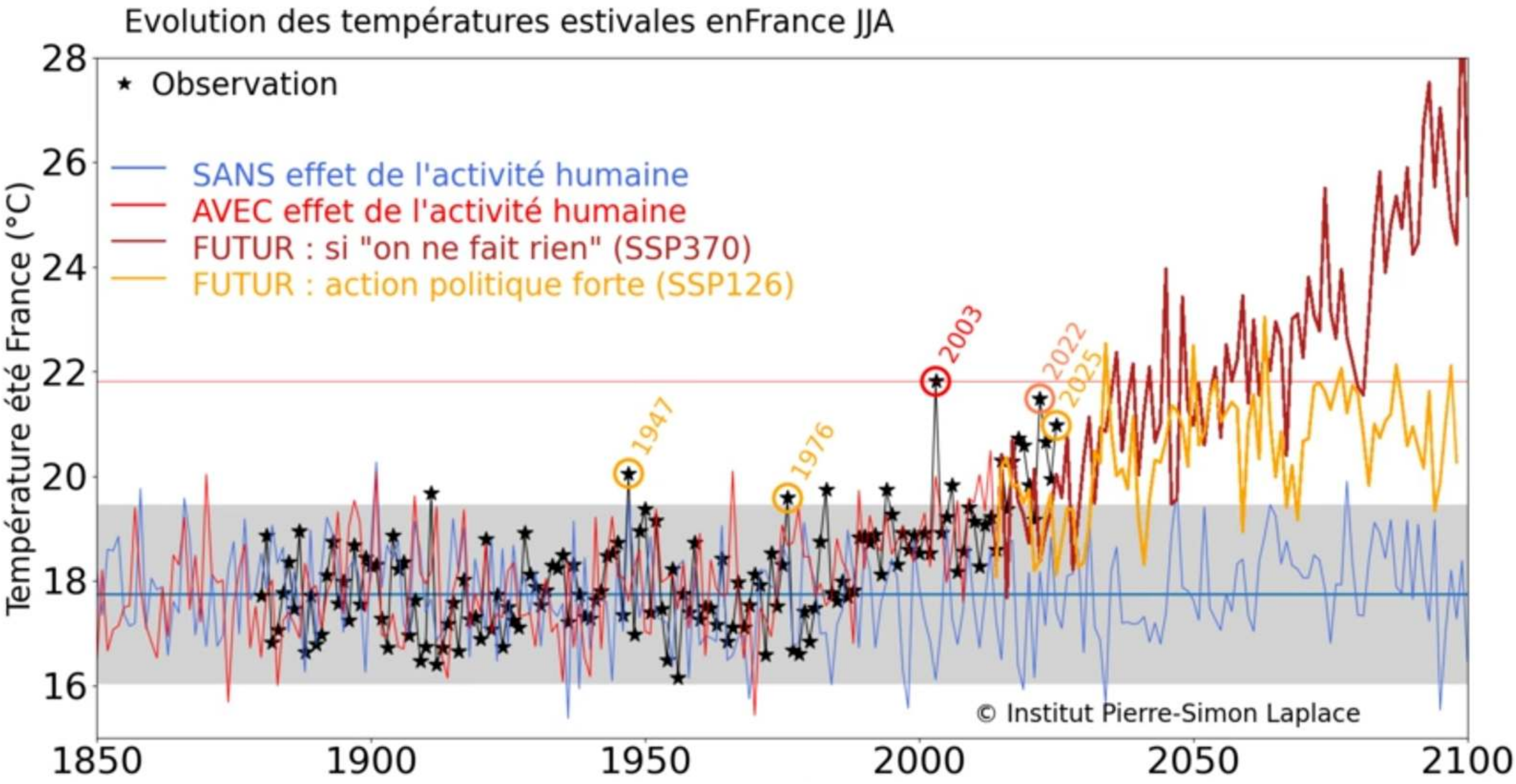
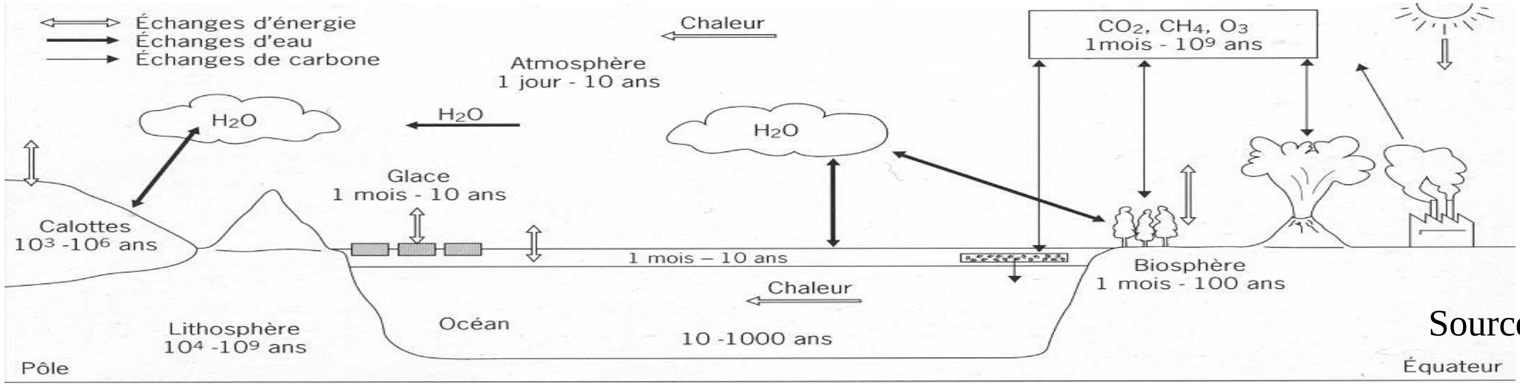
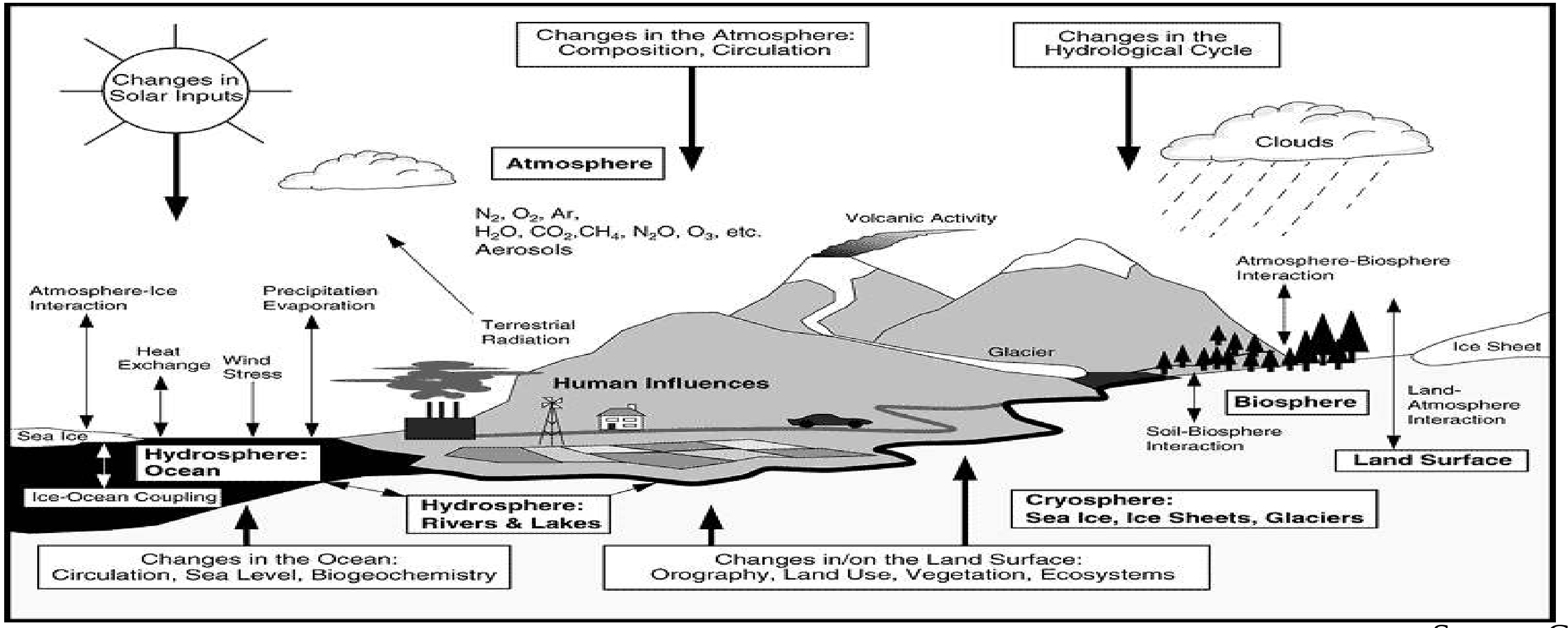


Climate : the world of appearances



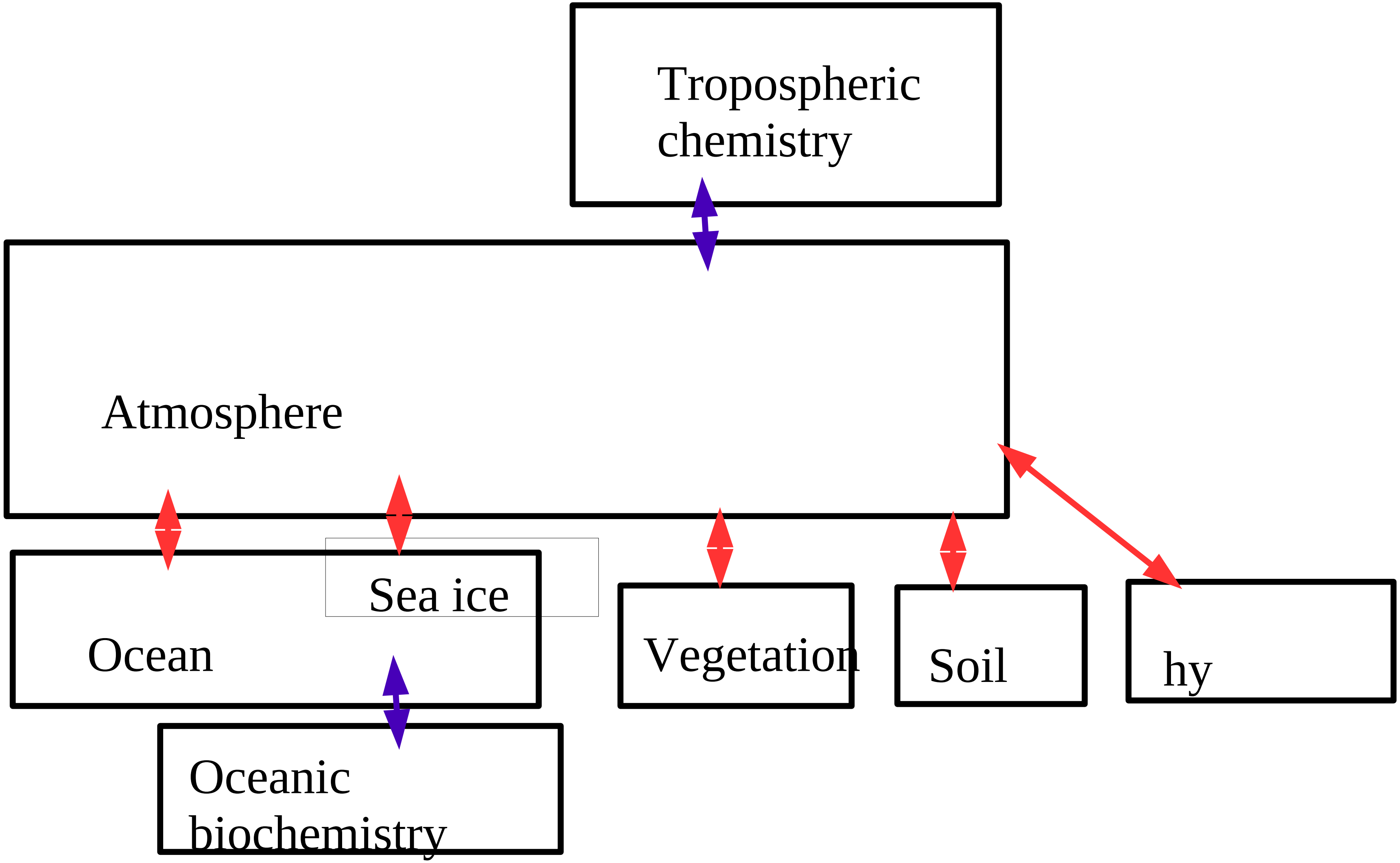
Source: S. Joussaume, 2000



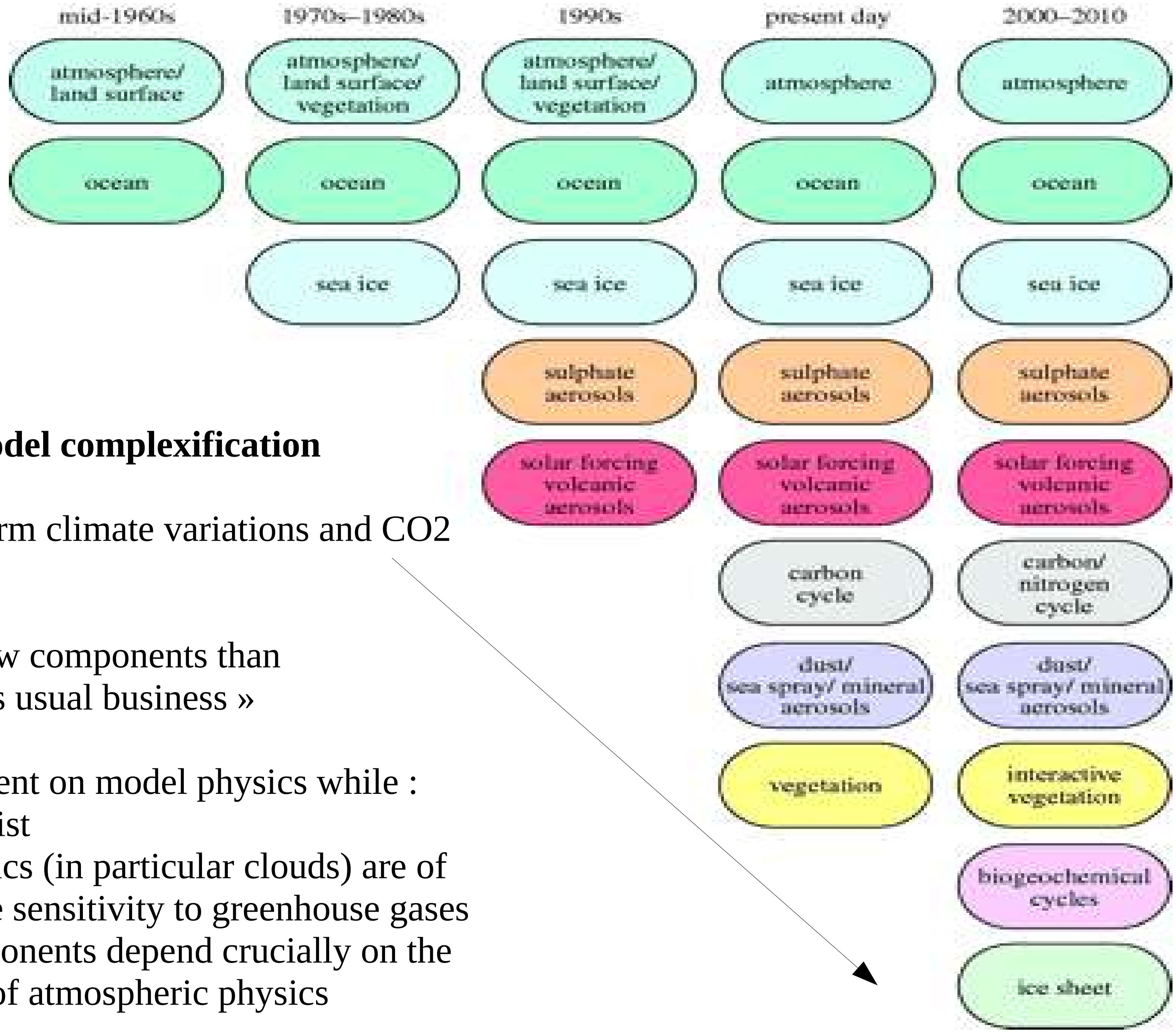
Source: GIEC, 2001

A complex system

Climate modeling : splitting in sub-systems



III. Climate system modeling



Priority given to model complexification

Motivated by long term climate variations and CO2 cycle

Easier to promote new components than improvements of « as usual business »

Not much improvement on model physics while :
→ strong biases persist
→ atmospheric physics (in particular clouds) are of first order for climate sensitivity to greenhouse gases
→ all the other components depend crucially on the good representation of atmospheric physics

NUM module MOCIS/WAPE

Part I (January) : work on numerical and physical aspects of the advection/diffusion equation

Coupling with composition : chemistry, aerosols, grenhouse gases
Conservation/transport equation : same for all transported species.
Shared by climate system models, pollution models, oceanic composition.

$$\frac{\partial q_i}{\partial t} + V . grad\, q_i = \frac{\partial q_i}{\partial z}\left(K_z \frac{\partial q_i}{\partial z} \right) + S_i$$

Advection

Turbulent diffusion

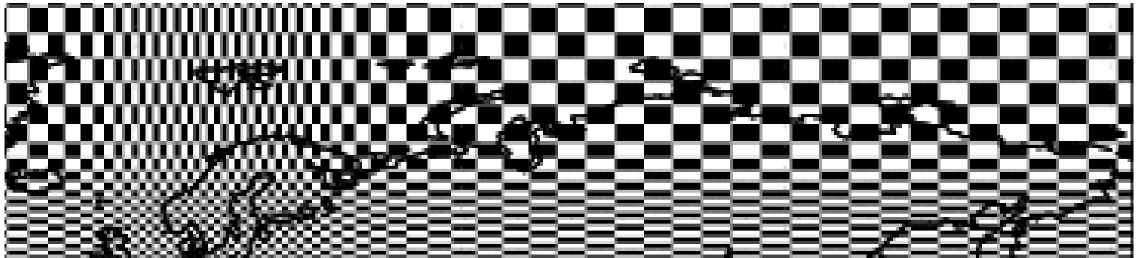
Sources / Sinks

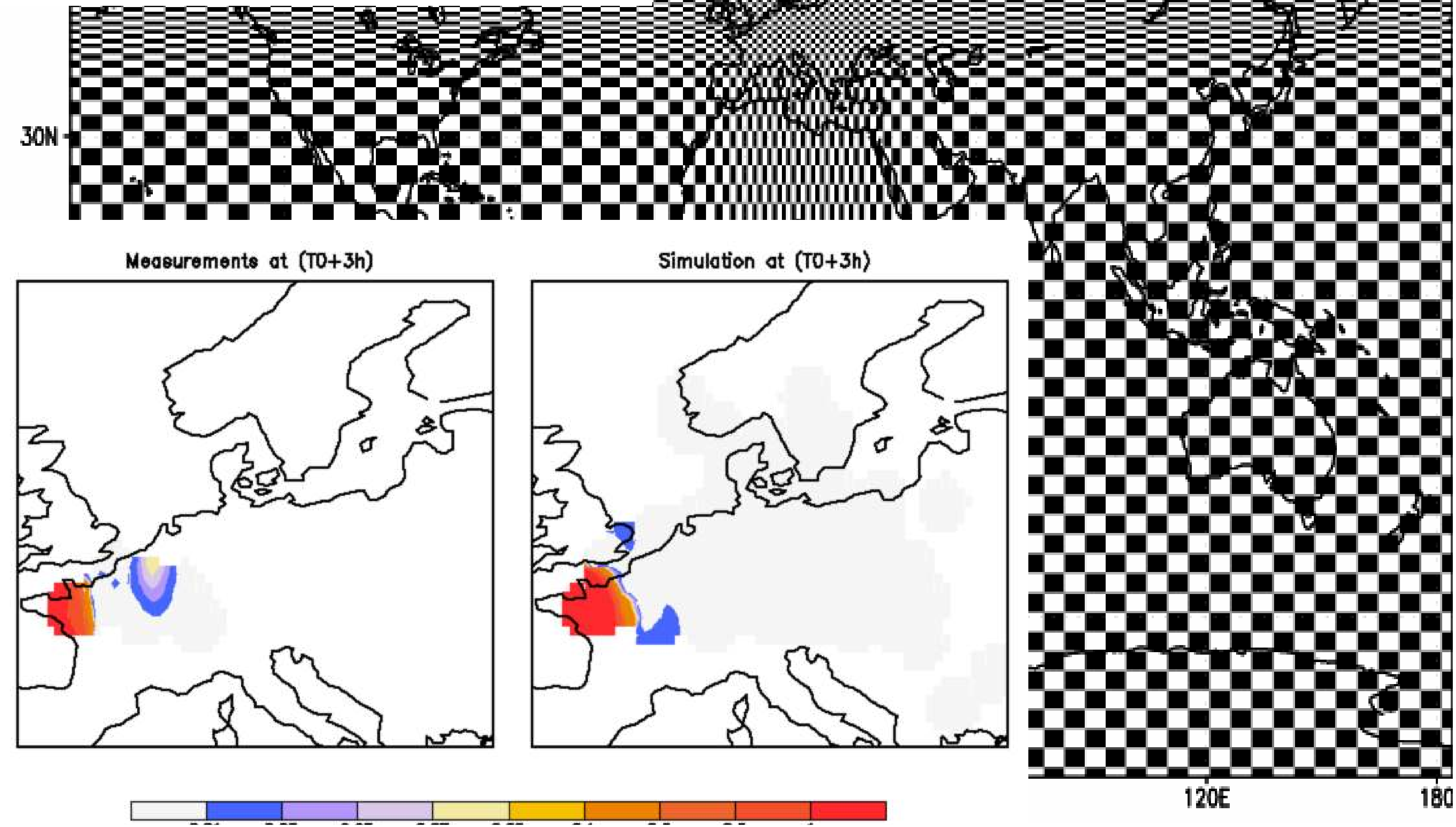
During practical work, work on this equations, assuming that the atmospheric dynamics is known (V and Kz). The problem is then linear in q.
We will explore numerical issues in this case.
Developing all the codes by yourself in Fortan

Part II (February) : « mini projets »

Atmospheric physics and dynamics with the LMDZ climate model
Oceanic physics and dynamic with the Nemo oceanic model
Numerical and dynamical issues in geophysical fluid dynamics

Transport evaluation :
Simultion of the dispersion of a pollutant emited
in french Britany (ETEX field campaing experiment)
Simulation de la dispersion d'un polluant émis
LMDZ model with streched grid and nuging by analysis





Summary

Circulation/transport atmospheric/oceanic models :

→ models (set of equations + numerical formulation and coding) which aim at simulating the space time evolution of the system.

→ The very same models are used for weather forecast and climate, but in very different operating modes.

→ 2 parts : explicit resolution down to a given scale (= a few grid cells) / parameterization of sub-grid scale processes.

→ For the explicit part : equation are relatively well established, and questions are more on the numerical and coding aspects.

→ For parameterizations, establishing the equations them selves one main issue of the research.

Climate system models (often called Erth System Models)

→ General circulation models include more and more physical processes : chemistry, aerosol micro physics, evolving vegetation, ...

→ Splitting in sub-systems allows teams to develop and asses independent specific models.

→ The system that couples the sub-systems requires specific development and evaluation.

Practical work :

→ Developing a simplified advection / diffusion model. From scratch. Fortran.

For those who are not familiar with Fortran, please go through
http://www.lmd.jussieu.fr/~hourdin/COURS/FORTRAN/Fortran.pdf